SIMULATION OF WATER QUALITY IN RIVER MAHI

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By
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to the
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TO

MY PARENTS

4.8.7

CERTIFICATE

Certified that the work presented in this thesis entitled, 'Simulation of Water Quality in River Mahi', by Deepak Ruchandani, has been carried out under our supervision and it has not been submitted elsewhere for a degree.

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ABSTRACT

A one-dimensional water quality simulation model which incorporates mass transport by longitudinal dispersion and advection is presented. The model simulates temperature, dissolved oxygen, and conservative minerals. Dissolved oxygen balance has been coupled with carbonaceous bio-chemical oxygen demand, nitrification and atmospheric reaeration. The model was used to simulate water quality parameters in Mahi river during relatively dry period of the month of May. Simulated results matched fairly well with the observed values.

CHAPTER 1

INTRODUCTION

Rapid urbanization and industrialization has left mankind with problems of waste disposal. Liquid wastes generated in a community and industrial liquid wastes generated in industries are disposed off in natural water bodies like streams,rivers or sea. As a result of rapid industrialization the waste disposal in rivers has increased and has been localized near urban and industrial areas, which leads to degradation of water in its physical, chemical and biological qualities. For many engineering purposes, the concentrations of dissolved oxygen (DO) and decomposable organic matter in the stream were used as indicators of water quality (Streeter and Phelps, 1925). Because of complexities of various industrial wastes discharged into rivers, complex reactions and inter-relationship of various mechanisms including nitrification,oxygen uptake by oxygen demanding chemical wastes, etc. need to be coupled in assessment of dissolved oxygen balance in water body.

For the assessment of the extent of pollution in rivers, costly and time consuming water quality surveys are being under-taken and decisions for anticipated conditions in future are carried out usually by intution and experience

gained for similar conditions elsewhere. Engineers have constructed models to study such complicated systems. Modelling and simulation are techniques frequently used (and sometimes abused!) in today's scientific and engineering investigations.

A model may be thought of as being a representation of a system in a form suitable for demonstrating the way the system behaves, while simulation involves subjecting models to various changes in such a way as to explore the possible effects of these changes on the real system. When properly applied modelling and simulation can result in considerable saving in both time and money.

The mathematical model is a mathematical representation of the major mechanisms in a natural system in such a form that a cause and effect relationship can be analytically approximated. A complicated system like river system (for Water Quality Analysis) may require the combination of several mathematical models. These models can be transformed in such a way that output of one model can be used as input to the other and incorporated into a computer program to form a computerized simulation model.

1.1 Objectives of the Present Study:

The present investigation was undertaken to construct a mathematical model for predicting dissolved oxygen concentration and other water quality parameters in Mahi River System,

which receives industrial wastes from industries near Baroda. These industries are Gujarat Refinary, Gujarat Industrial Development Corporation Estate, Gujarat State Fertilizer Corporation, Indian Petro-Chemical Ltd., Suhrid Geigy (a pharmaceutical firm), Universal Dye Stuff. etc.

Rapid development in production in these industries has caused increased pollution in river Mahi. National Environmental Engineering Research Institute (NEERI), Nagpur carried out Mahi river survey in 1972-74. The work was sponsored by Gujarat State Public Health Department. NEERI proposed to construct an open channel to carry waste from industries mentioned above to much down-stream in estuarine region of Mahi river (Baroda Effluent Channel Project, Ref.2). It was sought to suggest in the present study the feasibility and need for constructing the channel.

On the Mahi river, there is a multi-purpose dam Kadana. Another multi-purpose project is under execution on Panam river, a major tributary of Mahi river. It is intended to evaluate quantitatively the water-quality oriented alternatives such as waste treatment level of combined waste from above mentioned industries versus flow augmentation from Kadana and Panam reservoirs in the Mahi river system.

CHAPTER 2

LITERATURE REVIEW

Environmental considerations have concerned water resource planners for many years. In the last 10 years, public interest has caused significantly increased efforts towards development of numerical techniques for analysis of water quality conditions in water resources systems.

2.1 Development in Modelling:

Finite element model is one of the common methods in modelling river system. Finite element model of a stream system consists of a series of elements as shown in Fig. 2.1 corresponding to a discrete stream segment arranged so that the output from one element becomes the input to the next. The transfer function is determined by performing a mass balance of a given water-quality parameter over a time interval, Δt, on a stream segment of cross-sectional area, A and of lengths Δx along x-axis.

2.1.1 Hydrologic Balance:

Assuming steady-state conditions, a hydrologic balance for the control volume (see Fig. 2.1) can be represented by,

$$Q_{i-\frac{1}{2}} - Q_{i+\frac{1}{2}} \pm Qx_i + P - E = 0 \qquad (1)$$

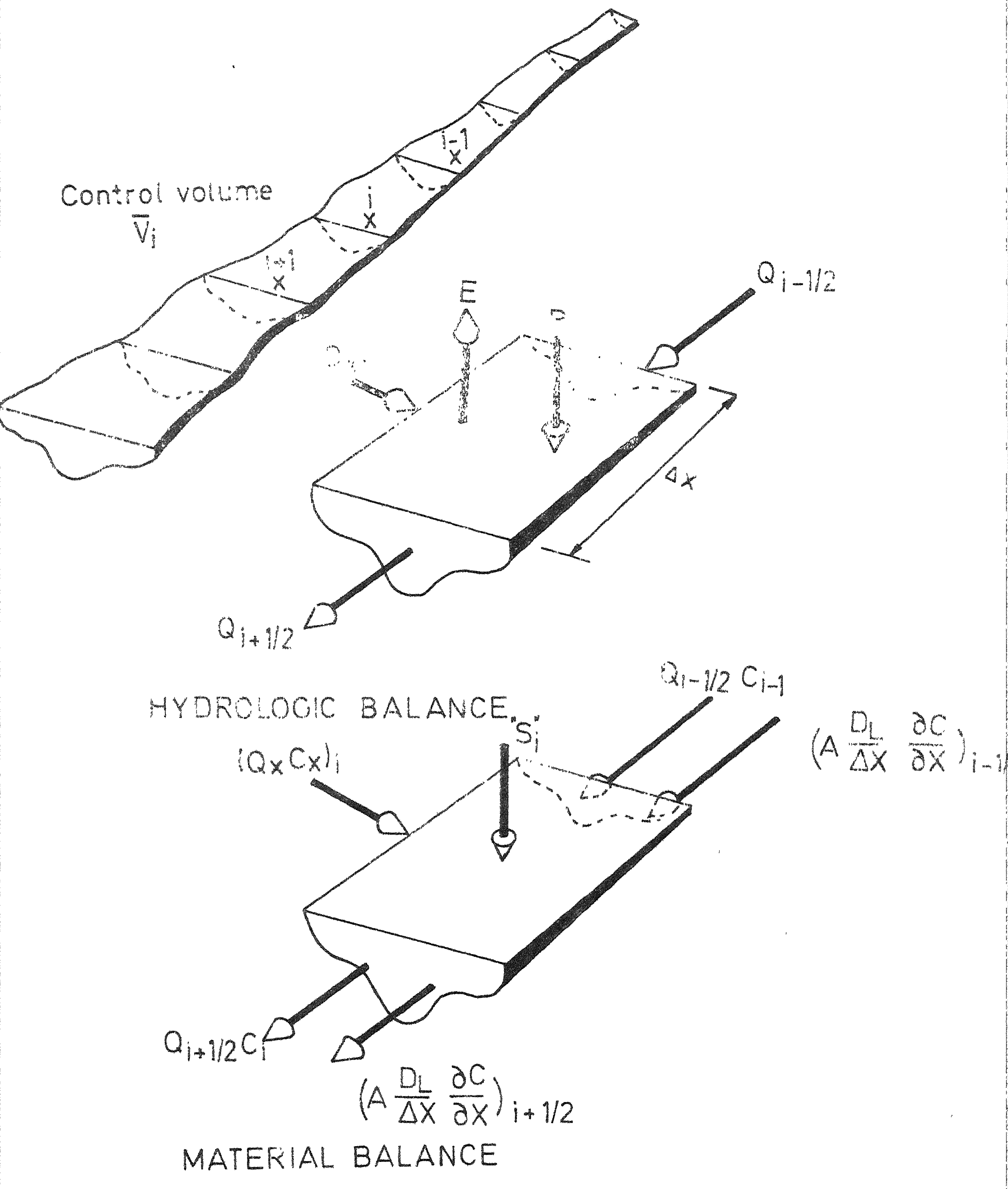


Fig. 2·1 Discretized stream system

where P is the precipitation rate, E is the evaporation rate. $Q_{i-\frac{1}{2}}$ is the flow entering i-th control volume, $Q_{i+\frac{1}{2}}$ is flow leaving i-th control volume and Qx_i is the run-off entering or leaving i-th control volume.

2.1.2 Material Balance:

In a river system, material balance of constituent is carried out by balancing mass entering the control element, and mass leaving the control element. Mass transport of constituent is accomplished by advection and dispersion. Dispersion represents the combined effects of density differences and velocity gradients. Assuming only longitudinal dispersion to be predominant a temporal distribution of a constituent within a control volume due to dispersion is given by,

$$A \frac{\partial c}{\partial t} = \partial \left(AD_L \frac{\partial c}{\partial x}\right) / \partial x \qquad (2)$$

where c = concentration of constituent under consideration, t = some point in time, x = some point along x-axis, D_L = longitudinal dispersion coefficient, A = cross-sectional area of the element.

Mass transport due to advection will result in reduction of the temporal change in concentration of a constituent. Then eq. 2 will become,

$$A \frac{\partial c}{\partial t} = \partial (AD_L \frac{\partial c}{\partial x}) / \partial x - \partial (A\bar{u}c) / \partial x \qquad (3)$$

where $\bar{u}$ = mean stream velocity.

Let 'S' be the sink or source strength of a constituent under question. Then mass transport equation will be,

$$A \frac{\partial c}{\partial t} = \partial (AD_L \frac{\partial c}{\partial x}) / \partial x - \partial (A\bar{u}c) / \partial x \pm A'S' \qquad (4)$$

Eq. 4 is a linear, parabolic partial differential equa tion describing temporal and spatial variations in constituent due to longitudinal dispersion and advection.

For steady-state conditions,

$$\frac{\partial c}{\partial t} = 0$$

$$\partial (AD_L \frac{\partial c}{\partial x}) / \partial x - \partial (A\bar{u}c) / \partial x = \mp A'S' \qquad (5)$$

Equation 5 is a **sec.** order linear differential equation in which general boundary conditions are,

$$c(0) = C_o$$

$$c(x) = C_x$$

where C_o = the concentration of particular constituent at head water source and C_x = the concentration of constituent just downstream of the last element.

Solution technique for eq. 5 is described in Appendix A.

Longitudinal Dispersion:

Dispersion is basically a conservative transport associated with spatially averaged velocity variation, as opposed to 'diffusion' which is reserved for transport that is associated primarily with time-averaged velocity fluctuations.

Longitudinal dispersion in rivers is given by eq. 6 (Ref.12)

$$D_L = 22.6\, n\, \bar{u}\, D^{0.883} \qquad (6)$$

where D_L = longitudinal dispersion coefficient ft^2/sec. n = Manning's roughness coefficient tabulated for different types of river channels in Table 1. $\bar{u}$ = Mean velocity, ft/sec, and D = mean depth, ft.

Table 1: Values of Manning's 'n' roughness Coefficient After Henderson (1966).

Natural River Channels	n
1. Clean and straight	0.025 - 0.030
2. Winding with pools and shoals	0.033 - 0.040
3. Very weedy, winding and overgrown	0.075 - 0.150
4. Clean straight alluvial channels	$0.031\ d^{1/6}$

(d = size in ft.)

Typical values of dispersion coefficients are given in Table 2 (Ref.12).

Table 2: Typical Values of Dispersion Coefficients

System Classification	D_L ft^2/sec.
1. Flumes and small streams	0.03 - 3.0
2. Large rivers	3 - 300
3. Estuaries	300 - 3000

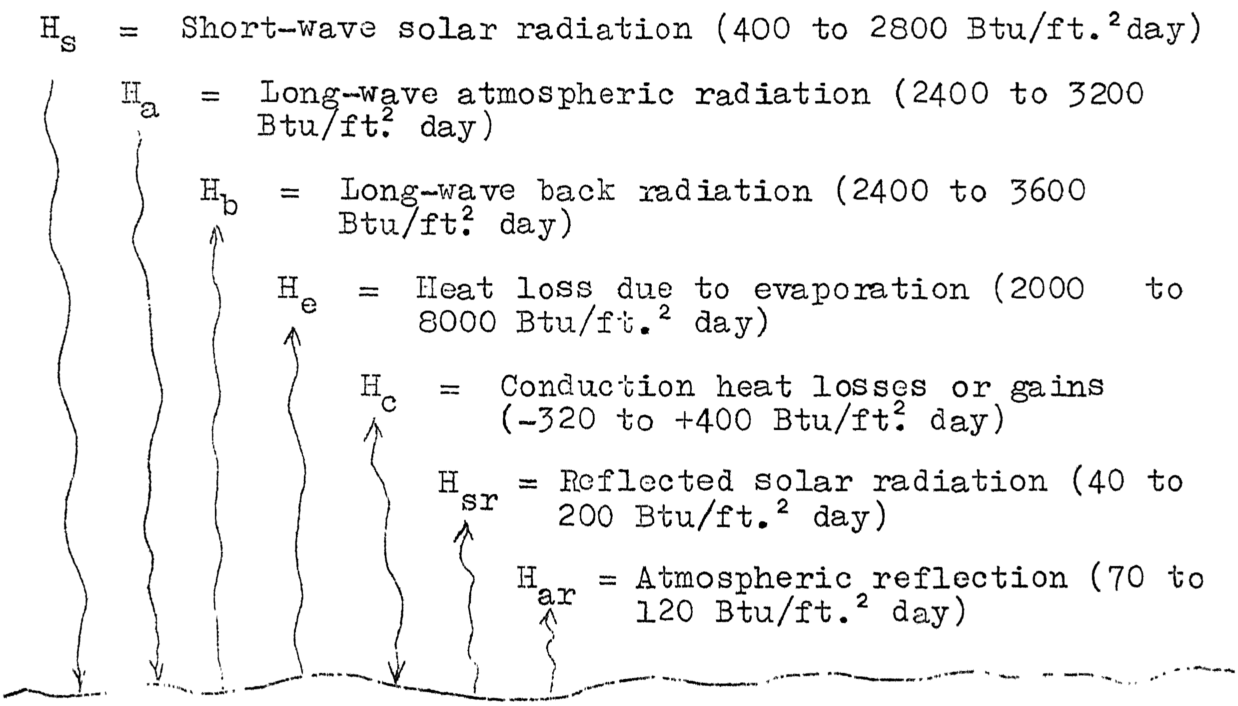
2.1.3 Sources and Sinks:

Following are the descriptions of sources and sinks for various non-conservative constituents as described in eq.4.

(i) Temperature:

In the thermal behaviour of a water body, it is essential to have a quantitative representation of the heat fluxes between the water surface and the atmosphere. These heat fluxes describe sources and sinks for computing variations in temperature. A body of water cools by losing heat to the atmosphere; conversely, it warms by gaining heat from the atmosphere. All bodies of water cool or discharge heat to the atmosphere by back radiation, evaporation and conduction, at the same time warming or receiving heat through short-wave solar radiation and long-wave atmospheric radiation.

It is illustrative to represent the net heat flux at the water surface as shown in Fig. 2.2. The range in magnitude of monthly average values of heat transfer are representative of northern latitudes.



FFig. 2.2: Net Rate at Which Heat Crosses the Air-Water Interface.

The expression that results from the summation of these various fluxes is,

$$H_N = H_{sn} + H_{an} - (H_b \pm H_c + H_e) \tag{7}$$

$$H_{sn} = H_s - H_{sr}$$

$$H_{an} = H_a - H_{ar}$$

where,

H_N = Net energy flux passing the air-water interface Btu/ft.^{2} day

H_{sn} = Net short-wave solar radiation flux passing through the interface after losses due to absorption and scattering in the atmosphere and by reflection at the interface, Btu/ft.^{2} day.

H_{an} = Net long-wave atmospheric radiation flux passing through the interface after reflection, Btu/ft.^{2} day.

H_b = Outgoing long-back radiation flux Btu/ft.^{2} day.

H_c = Convective energy flux passing back and forth between the interface and the atmosphere, Btu/ft.^{2} day, and

H_e = Energy loss by evaporation, Btu/ft.^{2} day.

Various heat fluxes and their transfer mechanisms have been well understood and are adequately documented in the literature by Edinger and Gever (1965) as well as in Ref. 12

A stream may be considered completely mixed in its transverse section if the heat exchange with the environment affects the water body practically instantaneously over its entire depth. Wunderlich (1969) found that the internal turbulence in many stream was sufficient to assume practically

instantaneous heat distribution from the surface downward. However, as velocities decrease and depths increase, this assumption, becomes less valid.

Thus, assuming complete mixing, Eq. 4 can be written with a source term for temperature as,

$$A \frac{\partial c}{\partial t} = \partial (AD_L \frac{\partial c}{\partial x})/\partial x - \partial (A\bar{u}c)/\partial x + A'S_H'/\gamma C_p \qquad (8)$$

where $S_H = H_N/D$ and D = Hydraulic depth of the stream, γ = weight of water, 62.4 lb/ft^3, C_p = Sp. heat of water 1.0 Btu/lb - ^{o}F.

The source term 'S_H', which has units of Btu/ft.^{3} hr, accounts for internal heat generation and all heat transferred across the system boundaries. That is, heat transferred across the air-water interface and heat conducted across mud-water interface. In absence of ground water flow, heat is transported across the mud-water interface only by molecular conduction which is relatively insignificant in comparison to surface heat exchange.

(ii) Dissolved Oxygen:

Source and/or sink term, as the case may be, for dissolved oxygen was defined by Streeter and Phelps' (1925) as,

$$\frac{dc}{dt} = K_2 (C_s - c) - K_1 L \qquad (9)$$

where c = Dissolved oxygen concentration in mg/l, C_s = Solubility of oxygen in water, mg/l, K_2 = atmospheric reaeration coefficient day^{-1}, K_1 = Carbonaceous BOD decay rate, day^{-1}, L = Carbonaceous BOD concentration, mg/l, C_s = Solubility of oxygen at given temperature is given by (Standard Method, 1971),

$$C_s = 24.89 - 0.426\ T + 0.00373\ T^2 - 0.0000133\ T^3$$

where, T = Temperature in ^{o}F.

For reaeration coefficients, six methods are available,

(1) Churchill et al (1962), $K_2 = 5.031 \dfrac{V^{0.969}}{H^{1.673}}$ (10)

(2) O'Conner and Dobbins (1958), $K_2 = 3.951 \dfrac{V^{0.5}}{H^{1.5}}$ (11)

(3) Owens et al. (1964), $K_2 = 5.346 \dfrac{V^{0.67}}{H^{1.85}}$ (12)

(4) Langbien and Durum (1967), $K_2 = 5.133 \dfrac{V}{H^{1.333}}$ (13)

(5) Thackston and Krenkel (1966), $K_2 = 24.95\ (1+F^{0.5})\ \dfrac{V^+}{H}$ (14)

where, K_2 = Reaeration coefficient, V = Stream velocity in m/sec., H = Hydraulic depth in meters, F = Froude number = $V/(Hg)^{0.5}$, V^+ = Shear velocity, m/sec. = $(H.S.g)^{0.5}$, S = Slope of water surface, m/m, g = acceleration due to gravity, m^2/sec.

When industrial wastes are discharged into river, many mechanisms occur in the water body, which are responsible for changes in the dissolved oxygen concentration. For example, ammonia discharged into river is oxidised to nitrites and which are in-turn oxidised to nitrates. During this process of nitrification there is considerable amount of oxygen demand.

Several workers, Thomann, R.V. (1972), Willis et al (1975), Ref. 17, have developed dissolved oxygen models which describe most of the mechanisms (physical, biochemical, chemical and biological) mathematically, which affect dissolved oxygen.

Hydraulic Engineering Centre of US Army Corps. (Ref.17) has developed the ecological model for dissolved oxygen as given below.

$$\frac{dc}{dt} = K_2 (C_s-c) - K_1L - KNH_3.NH_3.O_2NH_3-KNO_2.NO_2.O_2NO_2 - KDET (DET+S)\ O_2DET - \sum BIO.O_2R\ [BIOR + BIOG (\frac{1}{BIEFF} - 1)(1-EXF)] + \sum A(O_2P.AG - O_2R.AR) \qquad (15)$$

where c = Concentration of dissolved oxygen, K_2 = atmospheric reaeration coefficient, C_s = concentration of dissolved oxygen at saturation, K_1 = Rate of BOD removal by oxygen uptake, L = Concentration of ultimate BOD, KNH_3 = Ammonia decay rate,

NH_3 = Ammonia concentration as nitrogen, O_2NH_3 = Stoichiometric equivalence between oxygen and ammonia, KNO_2 = nitrite decay rate, NO_2 = nitrite concentration as nitrogen, O_2NO_2 = Stoichiometric equivalence between oxygen and nitrite, KDET = Detritus decay rate, DET = Detritus concentration, S = Concentration equivalent of organic sediment, O_2DET = Stoichiometric equivalence between oxygen and detritus decay, BIO = Biota concentration excluding algae, O_2R = Stoichiometric equivalence between oxygen and biomass respiration, BIOR = Biota respiration rate, BIOG = Biota growth rate, BIEFF = Biota digestive efficiency, EXF = Particulate fraction of total excrement, A = Algel concentration (i.e., phytoplankton and benthic algae), O_2P = Oxygenation factor for algal photosynthesis, AG = Algal growth rate, AR = Algal respiration rate.

(iii) Biochemical Oxygen Demand:

Sink equation for BOD is described as,

$$\frac{dL}{dt} = - K_1 L \qquad (16)$$

(iv) Ammonia Nitrogen:

$$\begin{aligned} \frac{dNH_3}{dt} = & - KNH_3 . NH_3 + KDET \ (DET+S) \ DN + \sum BIO.BION \\ & [BIOR + BIOG \ (\frac{1}{BIEFF} - 1)(1- EXF)] \\ & - \sum A.AP \ (AG.FNN - AR) \end{aligned} \qquad (17)$$

where BION = Nitrogen fraction of biota, AN = Nitrogen fraction of algae, FNN = Ammonia fraction of available nitrogen. Other symbols are same as explained in Eq. 15.

(v) Nitrate Nitrogen:

$$\frac{dNO_2}{dt} = KNH_3.NH_3 - KNO_2.NO_2 \tag{18}$$

where NO_2 = Nitrite nitrogen concentration

(vi) Nitrate Nitrogen:

$$\frac{dNO_3}{dt} = KNO_2.NO_2 - \sum A.AN.AG\ (1 - FNN) \tag{19}$$

Symbols are same as explained above.

2.2 Application of Simulation Models:

Most of the individuals or groups developing water quality simulation models during last few years have recognised their efforts as being only a first step in an evolutionary development of their respective models. However, many workers have put in their efforts in application of these models for real systems.

Rutherford and O'Sullivan (1974) have made attempts to predict water quality in the Tarawera river using the Streeter-Phelps' and various other first order models

but none of these could successfully predict the observed concentrations of dissolved oxygen.

The Box-Jenkins method, a time based technique for time series analysis is successfully used by Huck and Farquhar (1974) to model chloride and dissolved oxygen data for St. Clair River near Coruna, Ontario. This is thought to be the first application of the method to water quality data. The technique is demonstrated to be superior in this situation to either a frequency-based approach or a deterministic causative model. The description of the model building process includes the identification, estimation and diagnostic checking stages.

A one-dimensional model is presented by Aiba and Ohtake (1976) to simulate the spatial and temporal concentrations of PO_4-P in shallow and polluted river. The model incorporates, other than the convection and dispersion, various physico-chemical and biochemical reactions of phosphorous sinks and sources. With reference to field data on Tama-gava river, which penetrates through metropolitan area of Tokyo, the model is confirmed to represent the concentration of PO_4-P fairly well in the mid-region except for the mountaneous origin and its estuary.

Willis, R. et.al., (1975) have simulated water quality in Truckee River System in northern California and Nevada. They have incorporated the interaction of the dissolved oxygen resources of the water system with the nitrogen cycle, &chlorophyll a and carbonaceous biochemical oxygen demand. Also, conservative substances and phosphorous uptake by algae and coliforms are simulated by their model. Mass transport of constituents is accomplished by advection only.

Knowles and Wakeford (1978) have developed a comprehensive river water quality model, deterministic in type, in which eleven processes that were represented include nitrification, denitrification, photosynthesis, BOD decay, reaeration and others. This deterministic model has been used to predict river qualities in Blackwater System (part of the River Thames Catchment). It was tested under relatively dry conditions of 1973 and more normal conditions of 1974.

CHAPTER 3

SCOPE OF THE PRESENT STUDY

It is apparent from the literature that much insight has been developed in the field of simulation of water quality in rivers. In India, many of the important rivers are being surveyed for their water quality and enough information will be available soon to implement such simulation models on Indian rivers.

The scope of present study is to adapt to Indian conditions, the available know-how in the field of simulation of water quality. Sufficient data are available for Mahi river system in Gujarat. An attempt has been made in this study to simulate important parameters of water quality in Mahi river by using a suitable model.

The interrelation and interdependence of various mechanisms, which affect water quality, in aquatic environment are numerous. Mathematically it is possible to incorporate them in the simulation models as sources and sinks. However, it is difficult to quantify these sources and sinks in a real system. Hence, sources and sinks for various water quality constituents, which represent such mechanisms, have not been considered. A few of these sources and sinks are as follows.

1. Adsorption of various conservative and non-conservative substances on organic matter, turbidity-causing substances etc.

2. Denitrification, photosynthesis, BOD removal by sedimentation, benthic oxygen demand, effect of biological life on dissolved oxygen balance, dependence of solubility of oxygen on turbidity and chlorides etc.

Dissolved oxygen balance will be influenced directly or indirectly by whole of aquatic environment. It is difficult and beyond the scope of this study to take into account the entire aquatic ecosystem, while modelling such complex system.

These are several alternative strategies for control of ~~x~~ pollution of rivers. Some of them are :

(1) Augmentation of flow from storage reservoirs, (2) Treatment for waste loads before disposing the same into the river, (3) Allocation of discharge points for waste loads, (4) In-stream mechanical reaeration etc.

From among the above the following alternatives were selected for this study :

(1) Flow augmentation from Kadana and Panam reserviors,

(2) Treatment levels for the wastes being disposed in Mini

river and (3) Diverting the waste waters through a channel to dispose it in the estuarine region of Mahi river.

CHAPTER 4

METHODOLOGY OF STUDY

The present study was carried out in three distinct phases (i) Collection of data, (ii) Verification of model, (iii) Use of model as decision making tool. Before discussing these phases, a description of Mahi river system is given below.

The Mahi river originates from the Vindhya hills near about the village of Sardarpur in Dhar district of Madhya Pradesh. It flows through the State of Madhya Pradesh and Gujarat over a distance of about 600 km. before it joins the Gulf of Cambay. Some of the principal tributaries are Som, Anar, Panam, Karad, Meshri, Mini and Bhadar rivers. The section of Mahi river which is under present study is shown in Fig. 4.1 and schematic of model is shown in Fig. 4.2.

The Mahi river is the main source of water supply for the industrial zone of Baroda city and a supplementary source for the Baroda Municipal Corporation. On an average 25 to 30 mgd of water is derived from radial wells sunk below the bed of the river.

The industrial waste is disposed of in Mahi river through its tributary, Mini. Mini river originates at a distance of

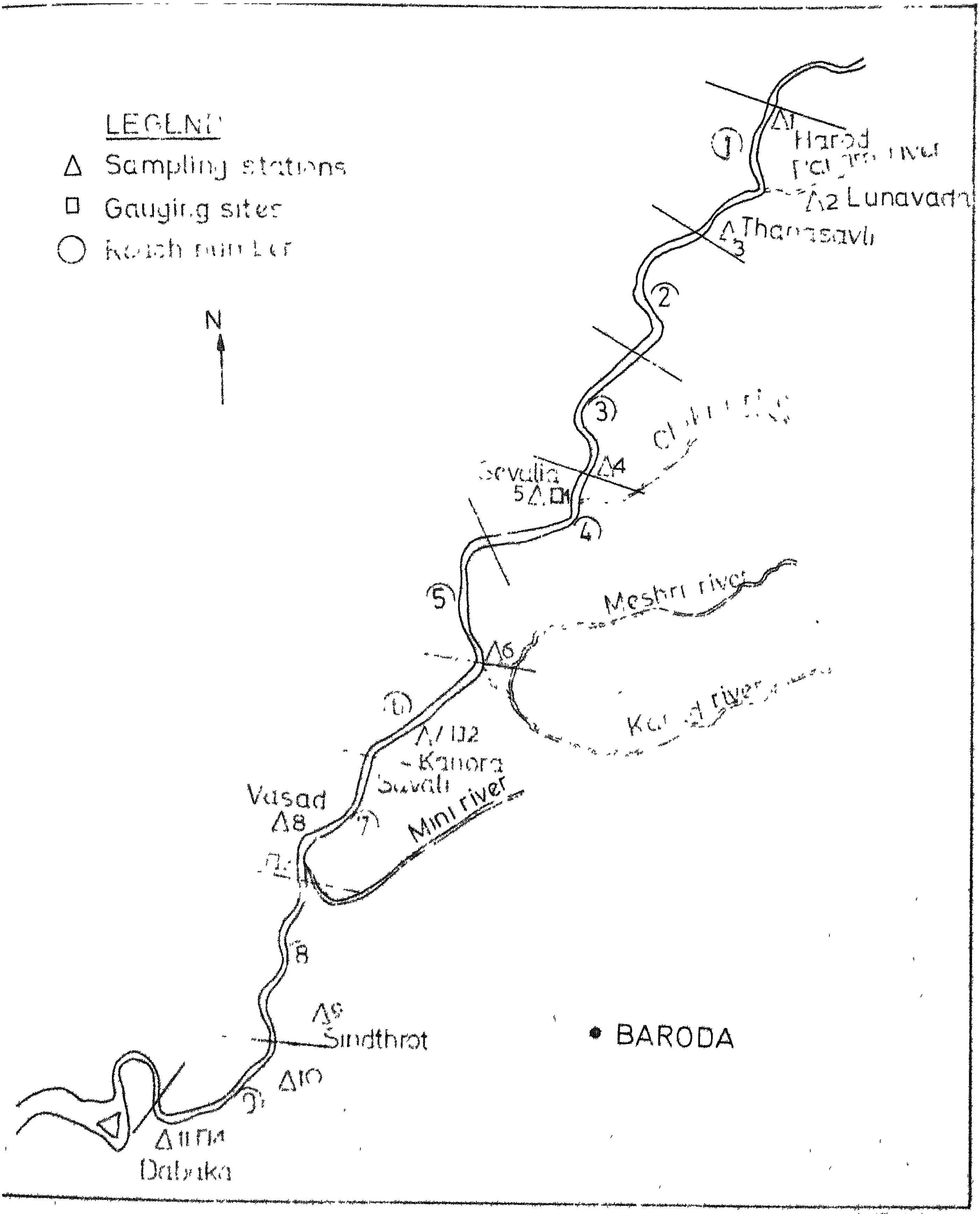


Fig. 4.1 Mahi river basin

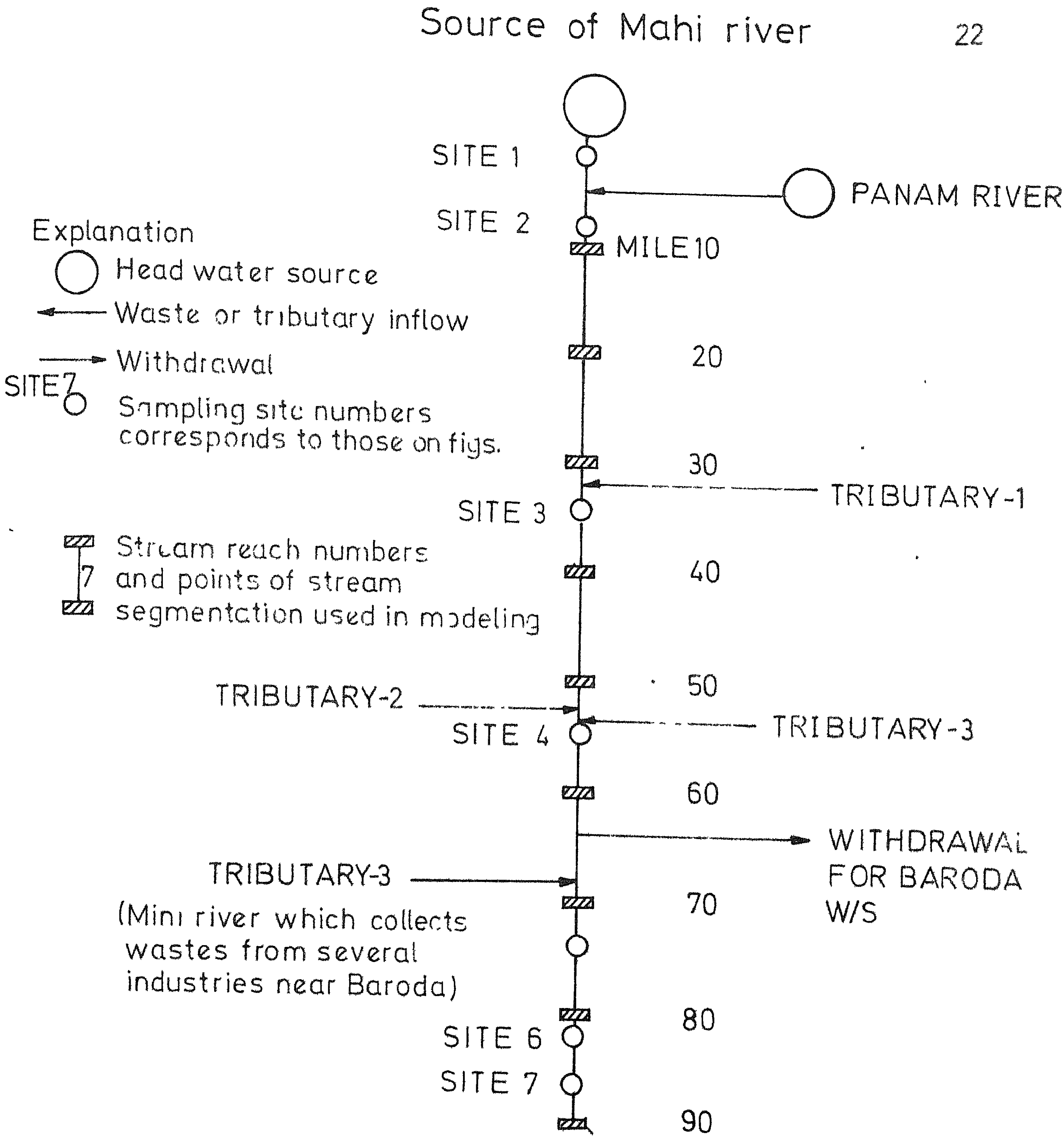


Fig.4.2 Schematic of model system

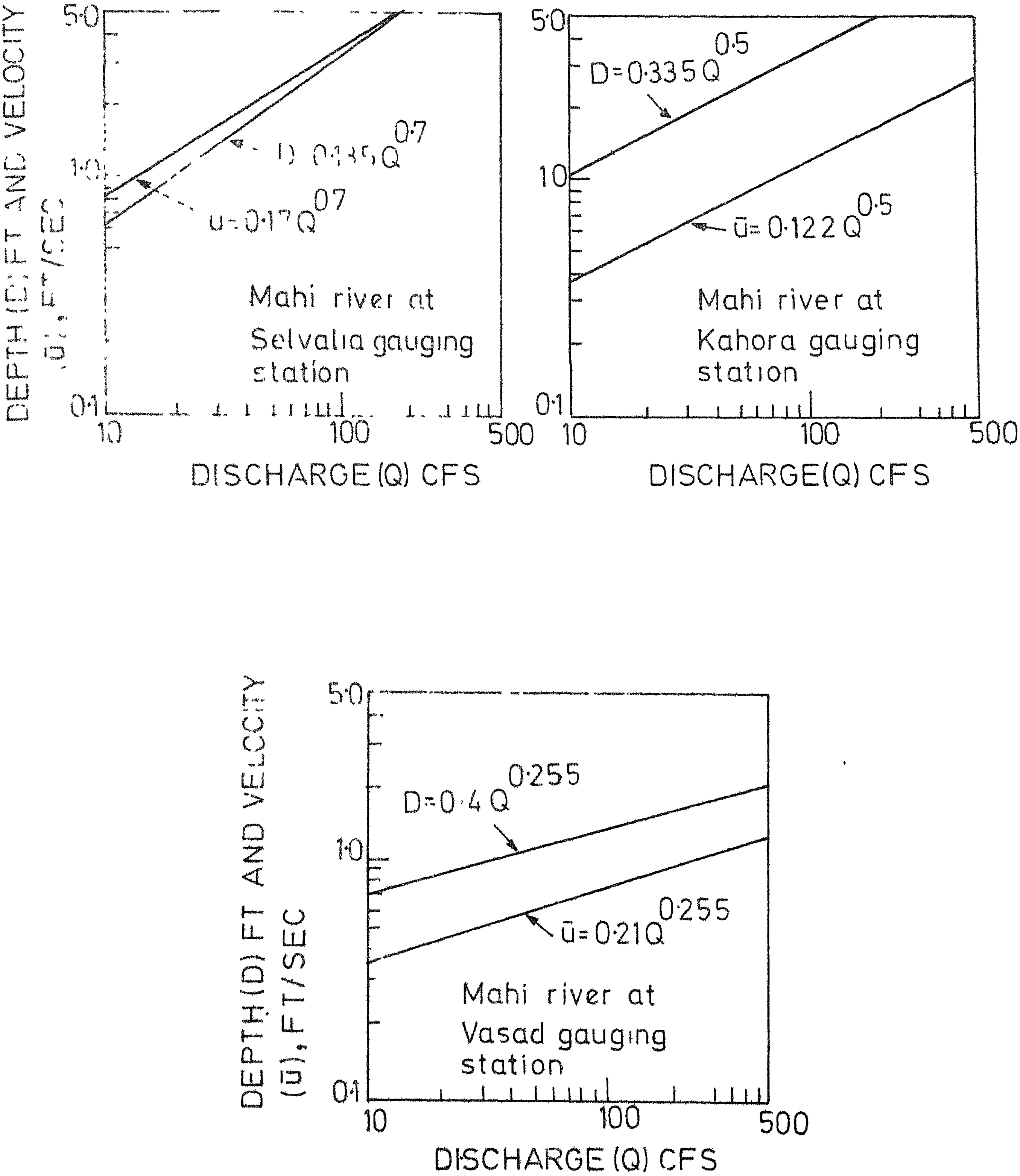


Fig.4·3 Depth velocity discharge relations for selected gauging stations

30 km. north east of Baroda. Its course is almost parallel to that of Mahi.

The total of 6 mgd waste water is discharged into Mini river from various industries. (Ref. 2).

4.1 Collection of Data:

Water quality, hydrologic data and local meteriological data were collected from various government organisations.

4.1.1 Hydrologic Data:

Average stream velocity and average depth at three guaging stations as shown in Fig. 4.1 were available for three different discharge conditions. These data were supplied by river guaging division of irrigation department, Government of Gujarat and Material Testing Division of Gujarat Engineering Research Institute, Baroda. Monthly average of flow rates in Mahi river at Kadana village just downstream of Kadana dam and monthly average flow rates in Panam river for 1977 were also supplied by Irrigation department.

The stage-discharge rating curves are prepared from the hydrolic data at three guaging stations. These curves (Fig. 4.3) are used to determine other hydraulic characteristics of the stream. Stage-discharge rating curves at Sevalia are used for first three reaches, that at Kanora

were used for next three reaches and same at Vasad were used for last three reaches.

4.1.2 Water Quality Data:

Water quality survey of Mahi river is being carried out by Material Testing Division of Gujarat Engineering Research Institute (GERI), Baroda. Water quality data at eight sampling points during 1978, as well as flow rates in tributaries were made available from the GERI, Baroda.

Data regarding quality of wastes were compiled from Baroda Effluent Channel Project Report. (Ref. 2). Water quality and flow rate data for wastes and tributaries have been presented in Table 3.

4.1.3 Local Climatological Data:

Dry bulb temperature, wet bulb temperature, atmospheric pressure and wind speed, data were available from Meteriological Observatory in Faculty of Science, M.S. University of Baroda. Five observations per day during May 1978 of above mentioned climatological data are used to route temperature in Mahi river.

Table 3: Water quality of tributary and waste inflows.

Tributary	Flow $ft.^3/sec.$	Temp ^oF	DO mg/l	BOD mg/l	NH_3-N mg/l	Norg mg/l	NO_2-N mg/l	Cl^- mg/l	$SO_4^=$ mg/l	TDS mg/l
1. Panam river	150.0	85^o	8.0	2.0	0.0	0.0	0.0	32.0	20.0	240.0
2. Kunda river	1.0	85^o	3.0	0.0	0.0	0.0	0.0	208.0	11.0	780.0
3. Moshri river	2.0	85^o	8.0	1.8	0.0	0.0	0.0	180.0	20.0	690.0
4. Karad river	1.5	85^o	8.0	1.8	0.0	0.0	0.0	0.0	70.0	812.0
5. Mini river	6.0	85^o	0.0	35.7	447.0	462.0	1.0	640.0	147.0	1300.0

4.2 Verification of Data:

Preliminary computation was carried out using Streeter and Phelps' model for dissolved oxygen balance. It is found to be inadequate for lower reaches on the downstream of confluence of Mahi and mini river.

Hence, model developed by HEC as shown in literature is used which includes nitrification also. This model is compared with the dissolved oxygen concentrations observed during May 1978. The model for conservative constituent is also tested by comparing observed concentrations of the constituent.

4.3 Use of Model as a Decision-Making-Tool:

It is concluded in the second phase of study that model is well compatible with the real system. Hence, three state variables, viz. flow augmentation, treatment efficiency of mini river waste and reduction in waste discharge from mini river are varied to know their impact on the real system.

Results of both the phases are presented and discussed in the next chapter.

Chapter 5

RESULTS AND DISCUSSIONS

As described earlier, 1978, summer data were used to verify the model. Simulated profiles of dissolved oxygen using various atmospheric reaeration coefficient formulae are shown in Fig. 5.1 through Fig. 5.5. All of these profiles have similar characteristics upto river mile 70. From river mile 70 to river mile 90 reaeration formula given by Churchill et.al. (1962) seem to be well comparable with the observed concentrations of dissolved oxygen. Hence, equation for K_2 given by Churchill et.al. (1962) is used in further analysis by using the model as a decision making tool.

Sudden increase in dissolved oxygen at river mile 5 is because of Panam river, which meets Mahi river at this point with very high flow rate and high dissolved oxygen concentration.

Similar rise at river mile 70 is observed. At this point water is withdrawn for Baroda water supply. Due to this reason, there is a significant reduction in depths. Because of this decrease, the reaeration coefficient is increased and hence, dissolved oxygen concentration rises at this point.

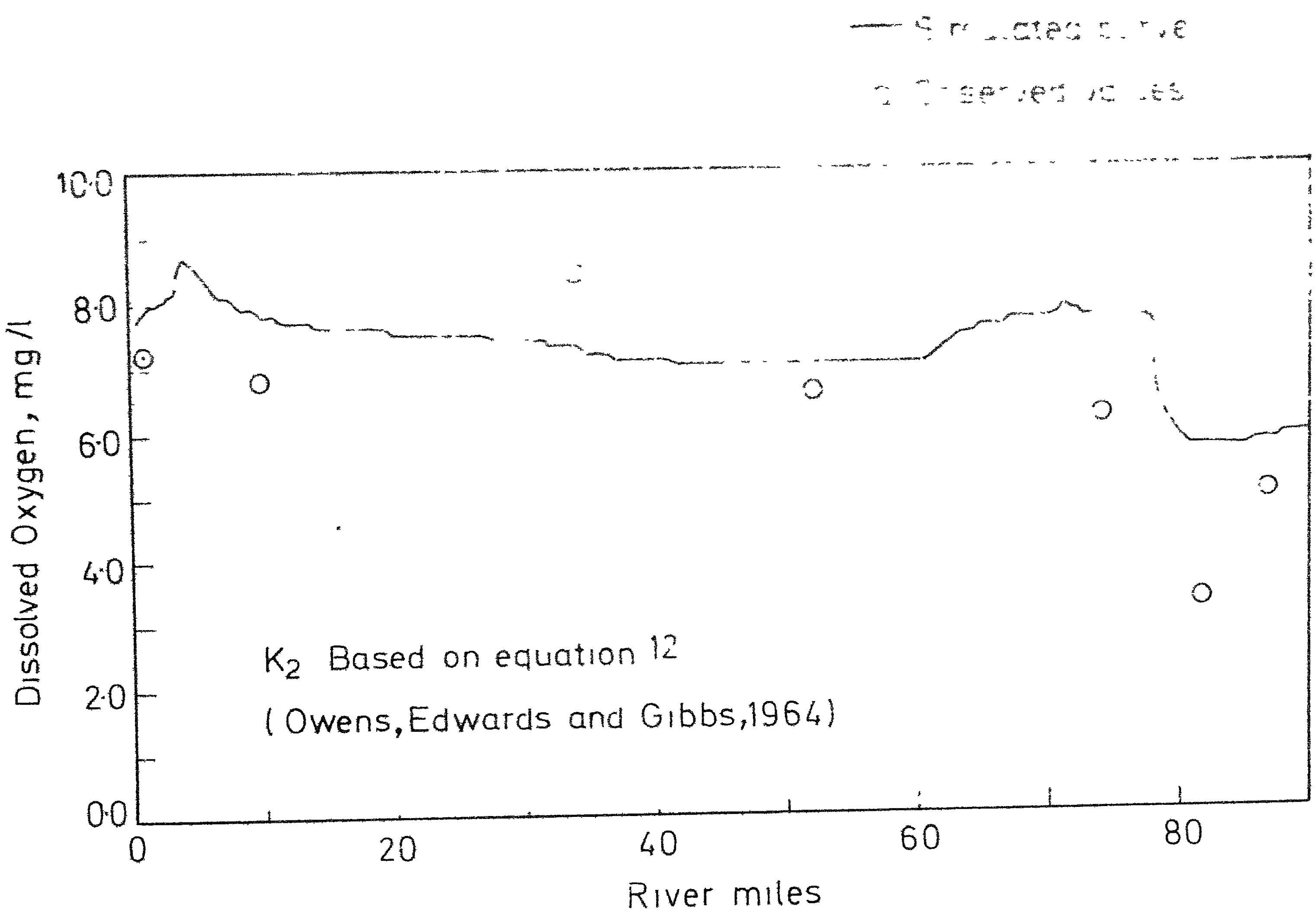


Fig. 5·1 DO Simulation results

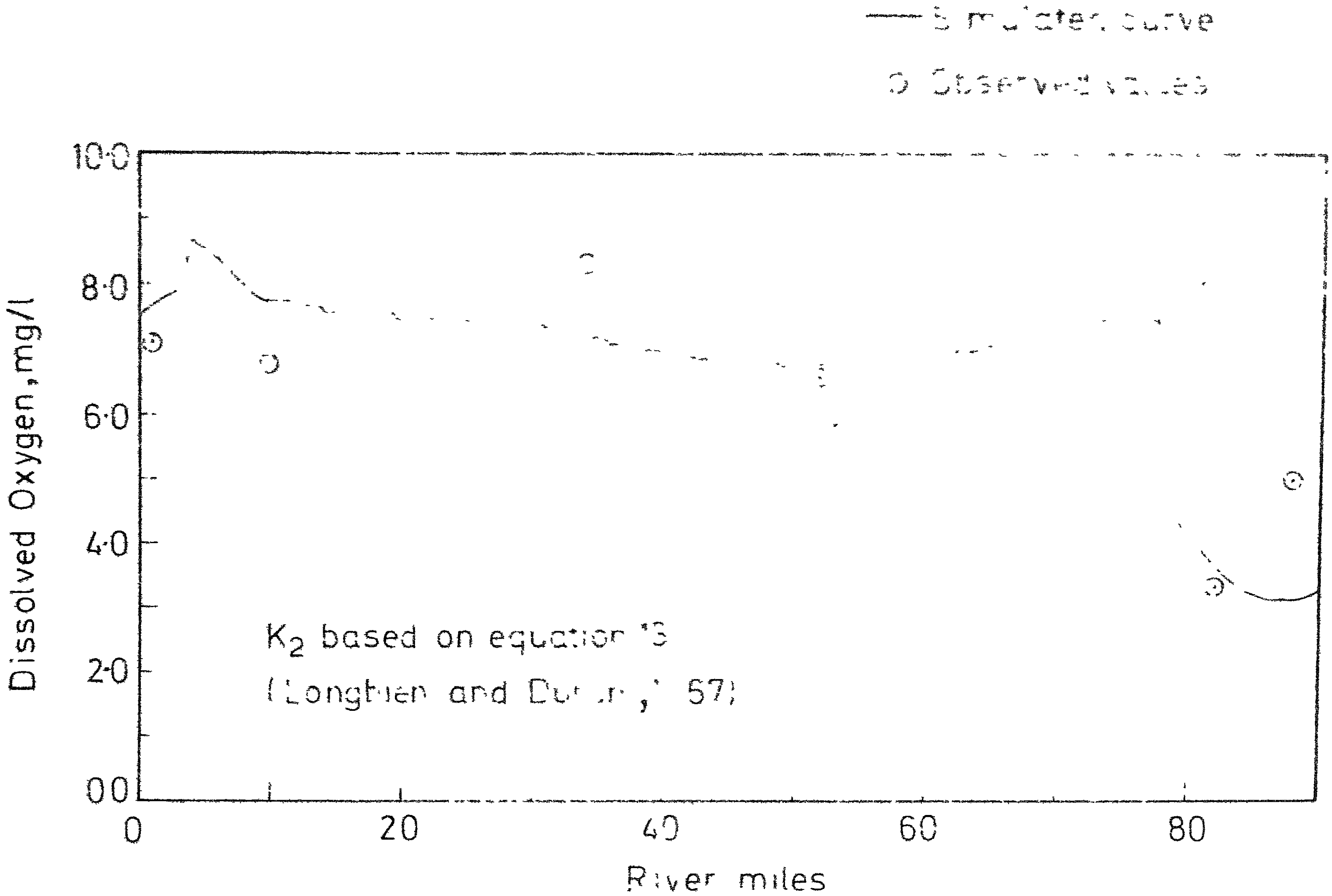


Fig. 5·2 DO Simulation results

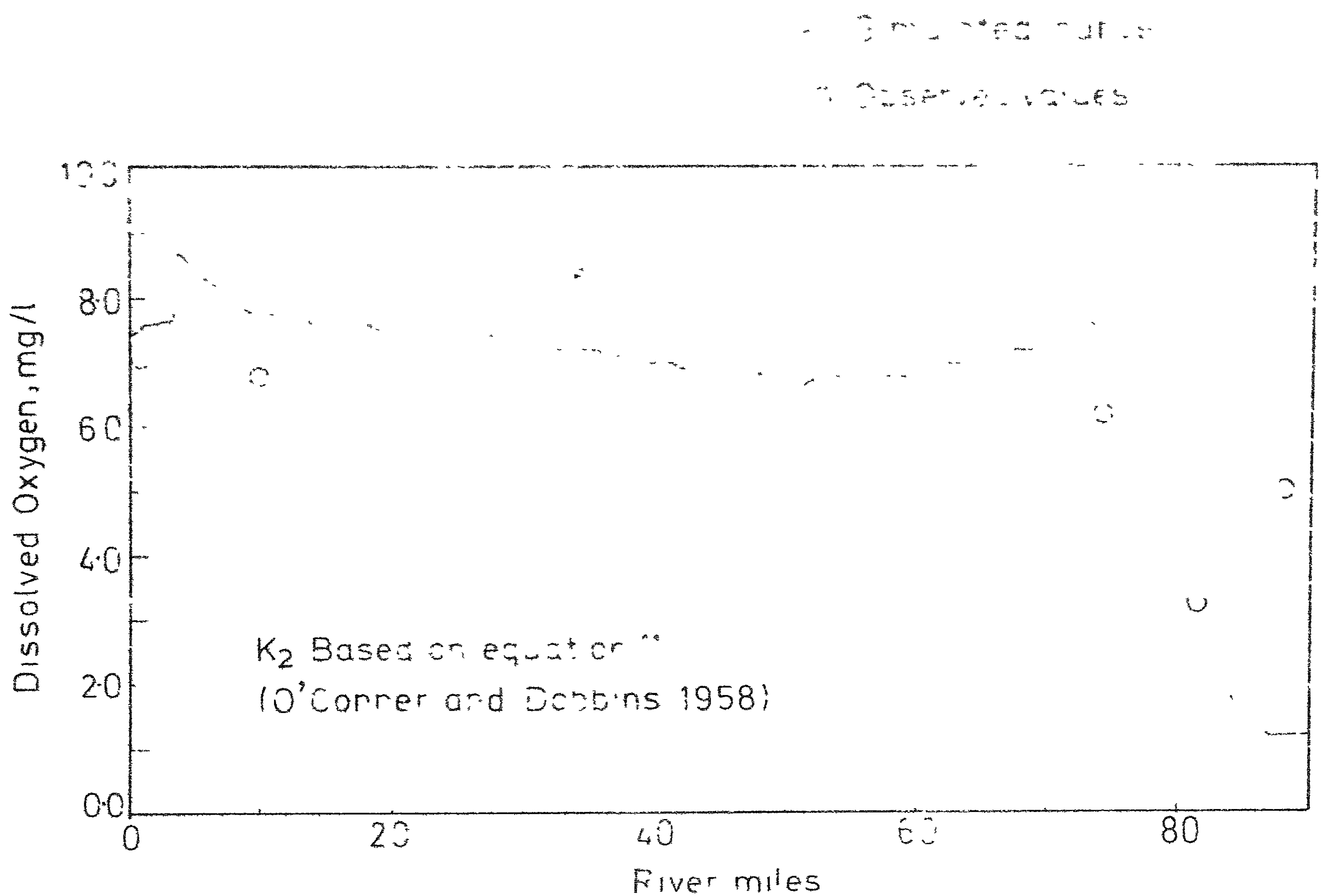


Fig 5·3 DO Simulation results

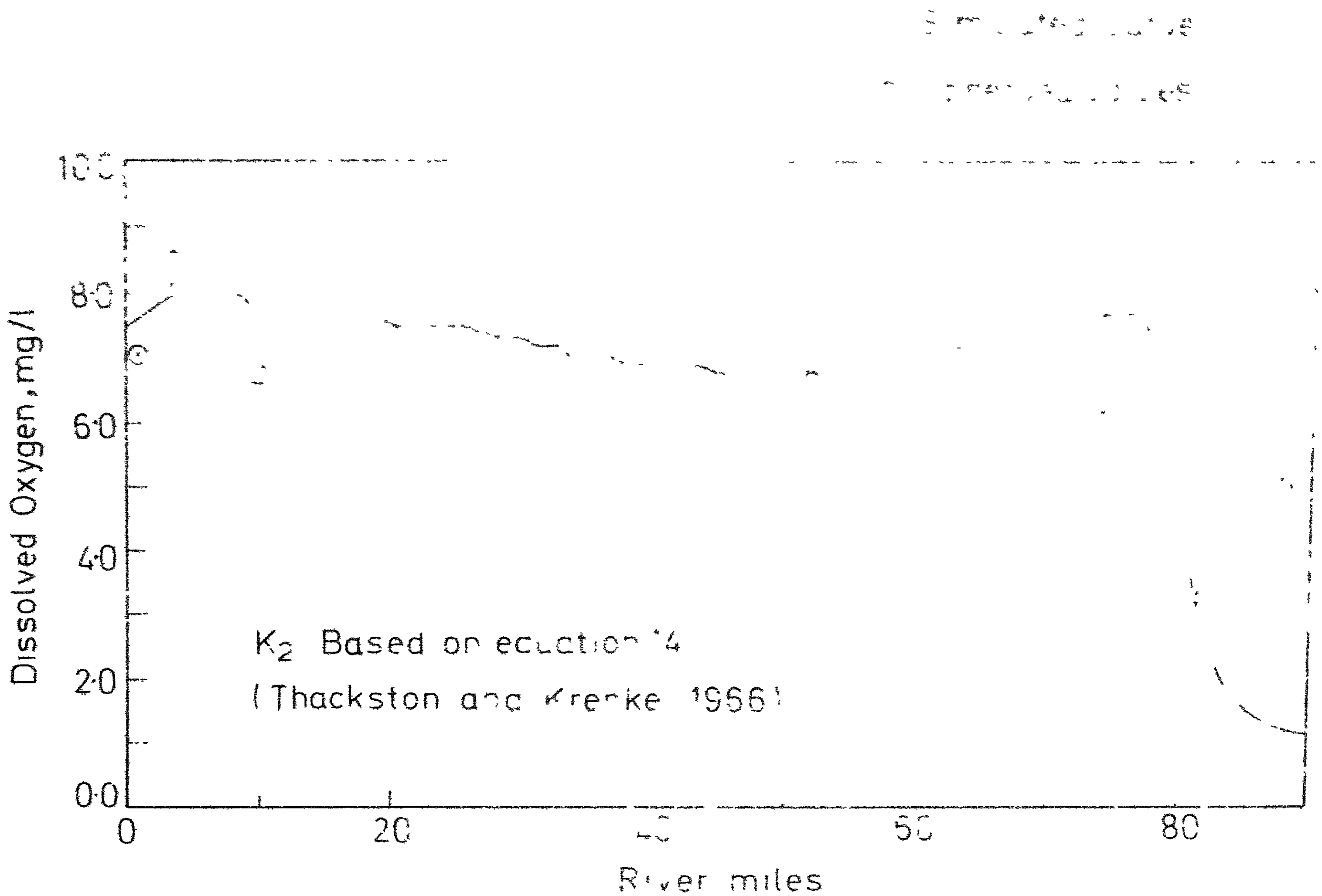


Fig.5·4 DO Simulation results

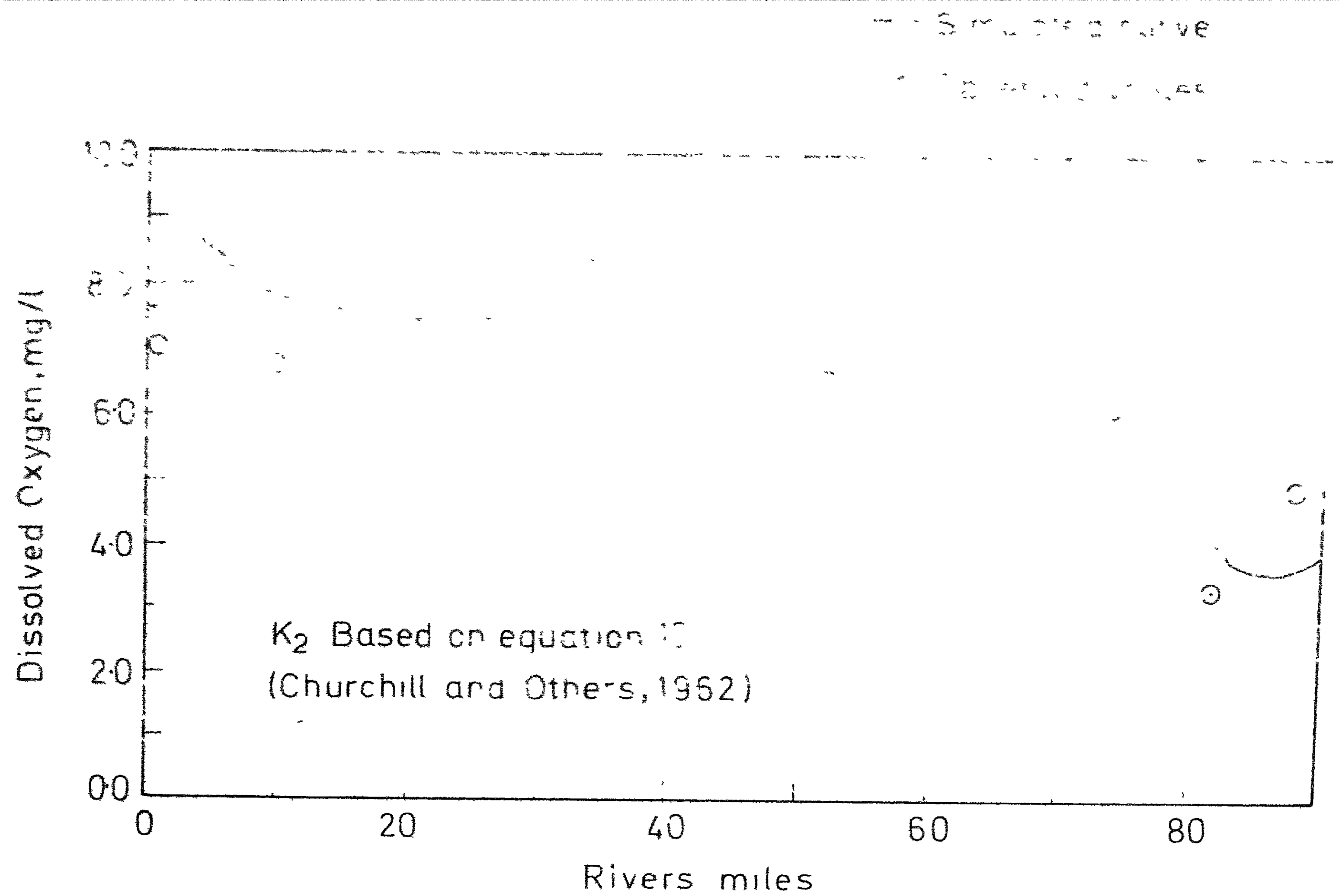


Fig. 5·5 DO Simulation results

Figs. 5.6 and 5.7 show simulated curves of conservative minerals and trace elements (Arsenic and Cyanide). All the computed profiles have much lower values than observed concentrations. This discrepancy may be due to following reasons. First, human errors encountered during collection and analysis of waste samples at disposal points. Secondly, in the model formulation, source and sink term is absent for conservative minerals, because it is difficult to assess the extent and location of removal or introduction of such conservative minerals in the river system. The discrepancies in the results of these minerals are also indicates there could be an unidentified source of pollution in the system, which have been overlooked due to ignorance.

Cynide is biodegradable at a very slow rate. Hence, assuming it to be a conservative material, concentration of cynide in river was simulated. The descrepancies in results of this constituent can be due to this assumption.

Phenol was also considered as conservative constituent. But it can be adsorbed on clay minerals or organic matter which are then removed from the system by sedimentation.

Arsenic concentrations were also simulated assuming it to be conservative. Sinks like uptake of arsenic by fishes, which are later removed from the system, have been overlooked.

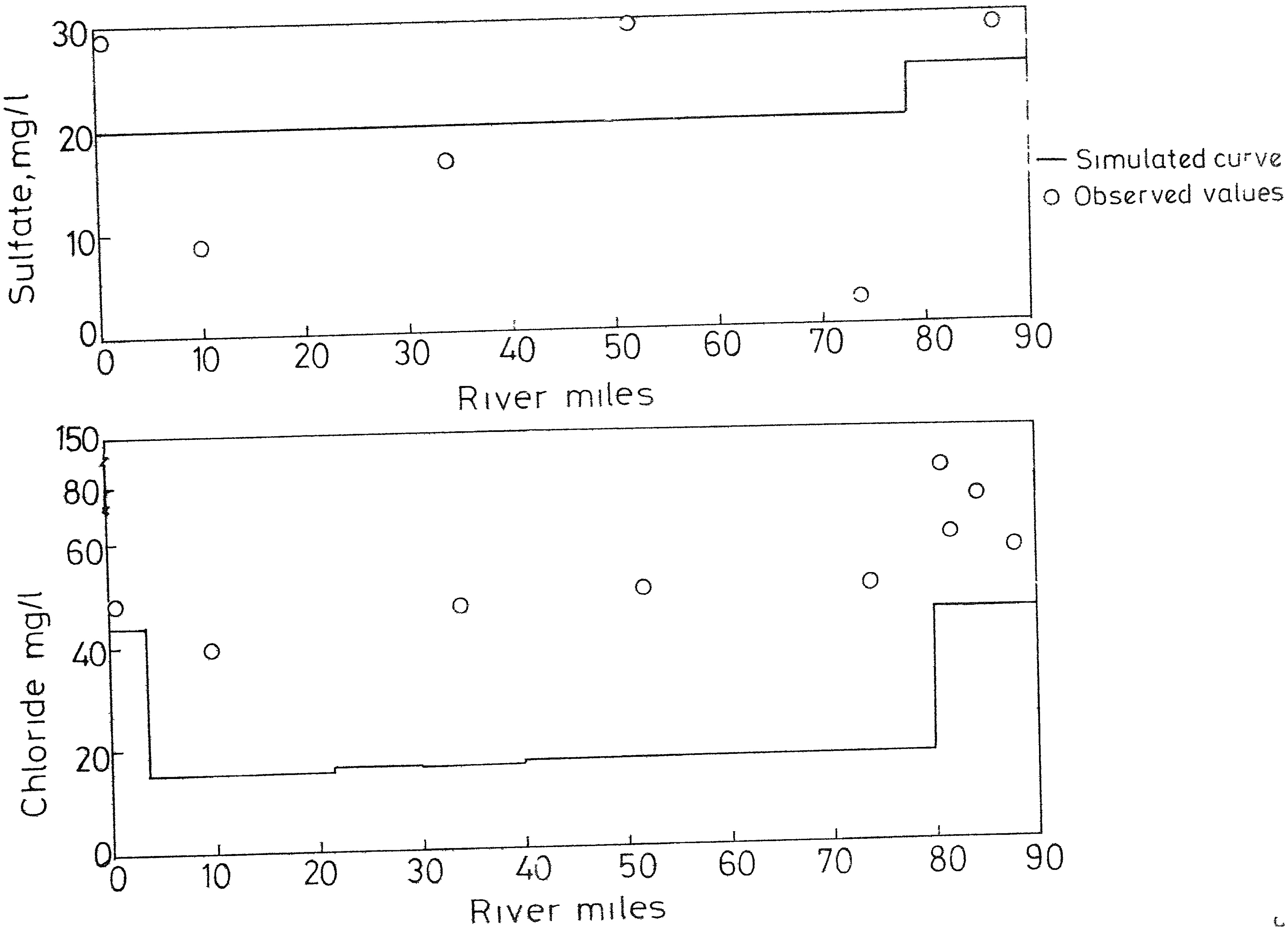


FIG.5.6 SIMULATION RESULTS

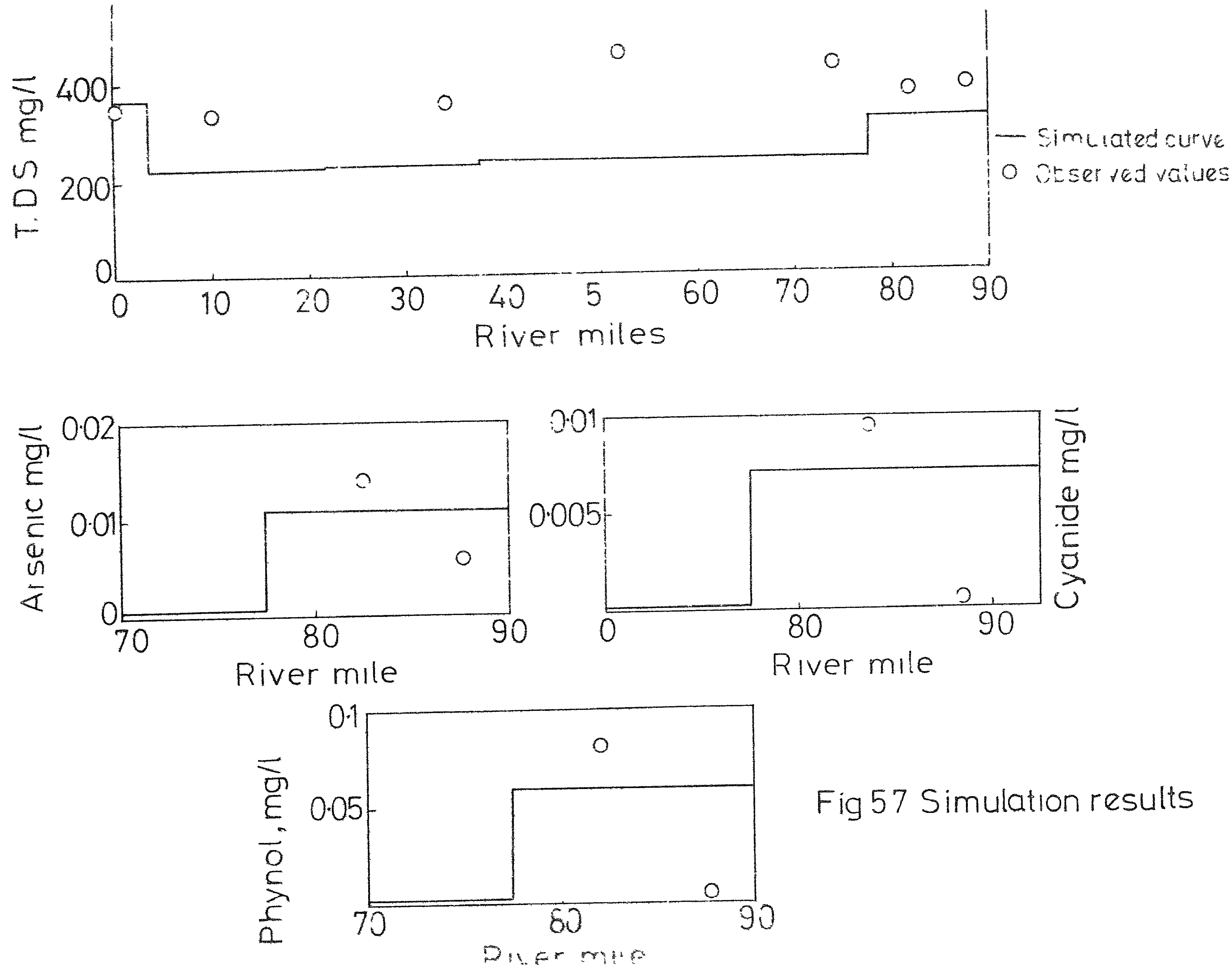


Fig 57 Simulation results

Thus, most of the discrepancies in the verification of model can be contributed to the ignorance of many sinks or sources, which are assumed non-existent in the model formulation. Also, availability of only limited number of observations at limited number of sampling points, errors involved in collection and analysis of samples are equal contributors of the total errors involved.

As explained earlier, the model uses stage-discharge rating curves for computing velocity and depth (Fig. 4.3) in each elements. These rating curves are constructed from a very limited number of observations and are used over long distances for computing hydraulics of river. Now, these variances in velocities and depths can significantly alter reaeration contribution to the dissolved oxygen concentration through dependence of the k_2 reaeration coefficient on velocity.

Various heat fluxes, that are transferred from water to air and visa versa are shown in Figs. 5.8 and 5.9. The simulated curve for temperature also lies, as shown in Fig. 5.9, lower than the observed values of temperatures at sampling stations. First, the simulated temperature values are average of temperature distribution in a day, while observed

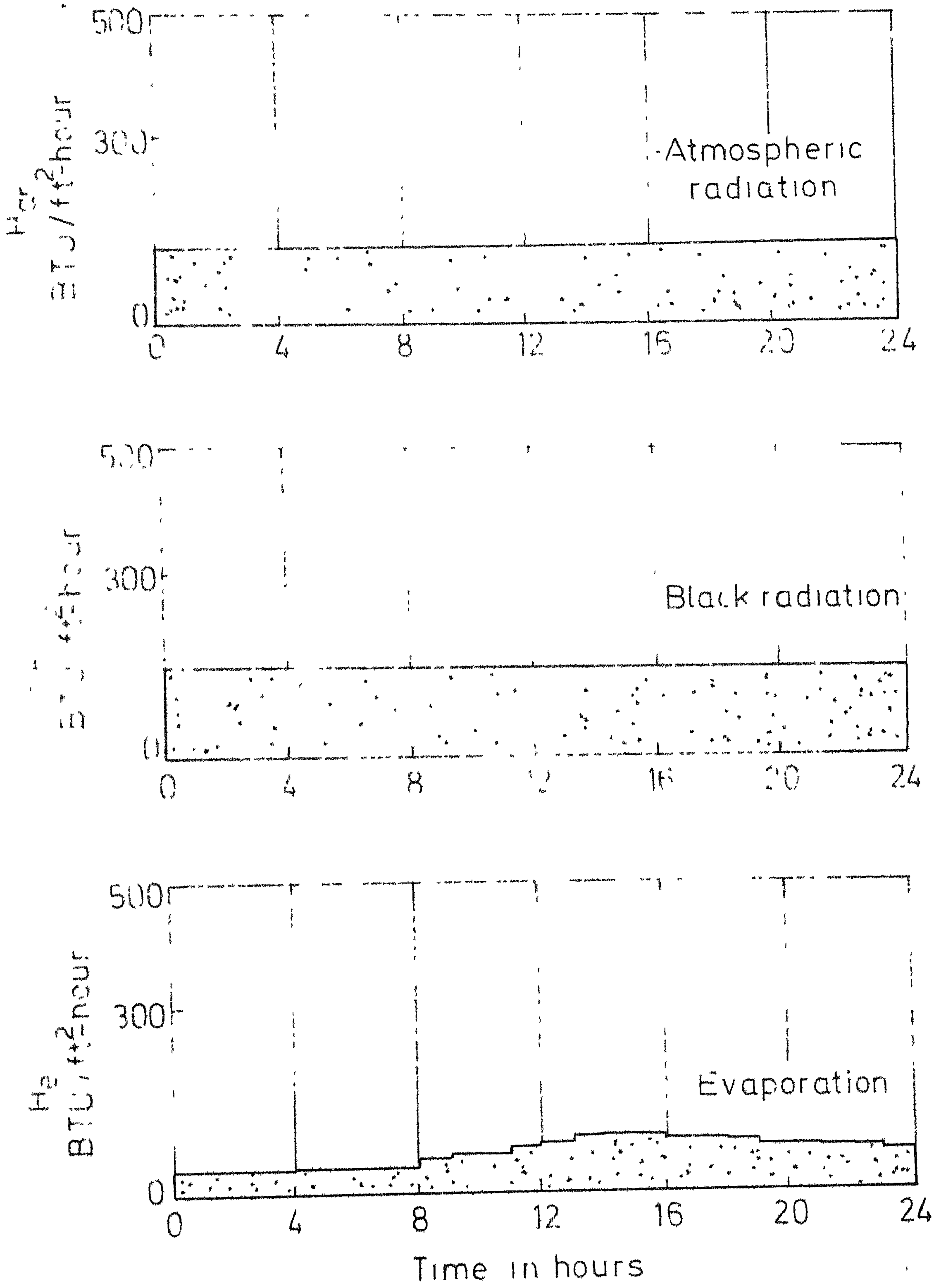
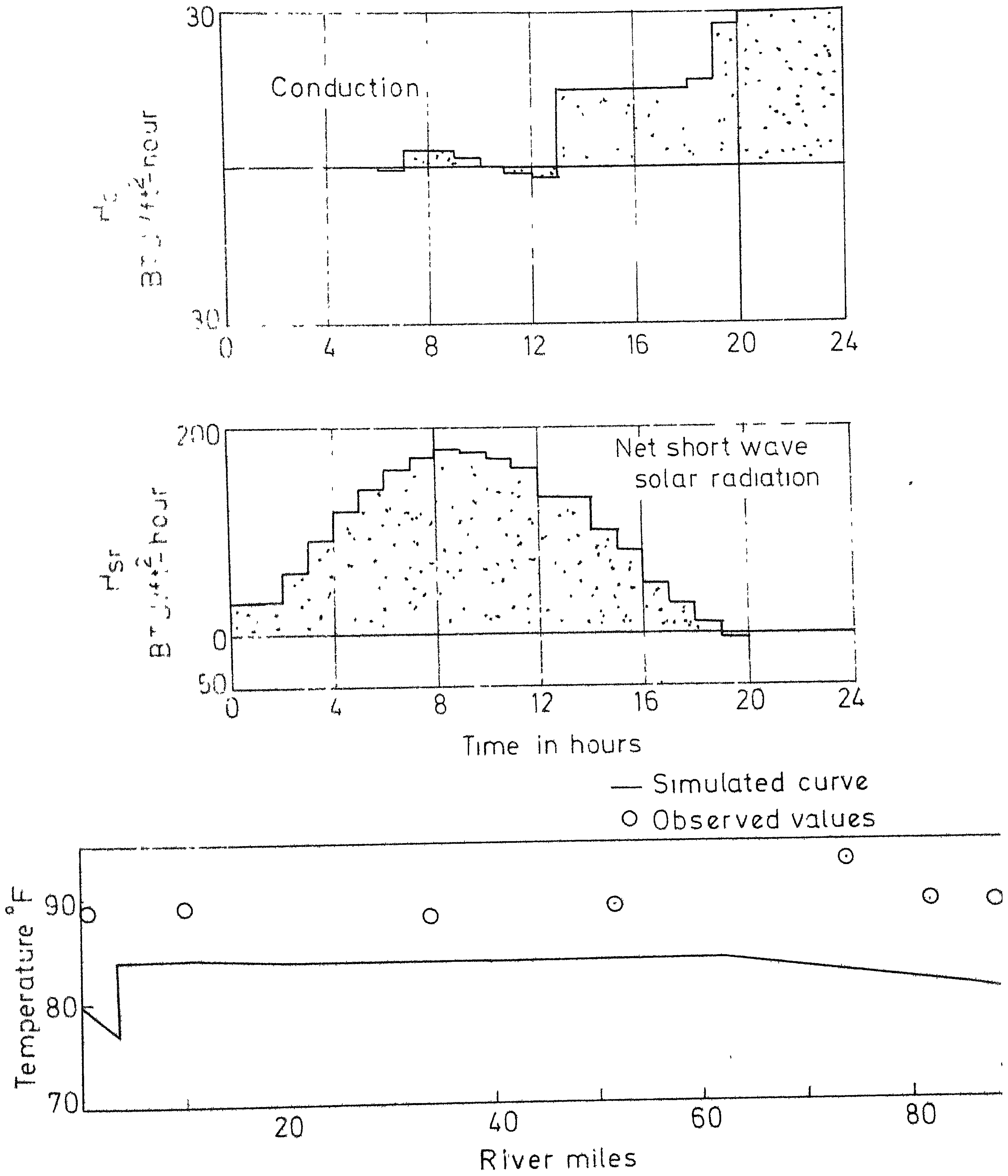


Fig.5·8 Diurnal stream temperature simulation results



30
Conduction
30
0
4
8
12
16
20
24
200
Net short wave
solar radiation
0
50
0
4
8
12
16
20
24
Time in hours
— Simulated curve
○ Observed values
Temperature °F
90
80
70
20
40
60
80
River miles

Fig. 5·9

values are grab samples normally taken in the afternoon. Descrepancy in these results is of the order of 5 to 10 ^{o}F. Secondly, local climatological data were collected in Baroda city and some of the sampling sites are 50 to 100 miles away from the metereological station.

Flow Augmentation:

Dissolved ~~x~~oxygen concentrations were falling below 4.0 mg/l after river mile 70. Flow augmentation was carried out from Kadana reservoir to upgrade the water quality in Mahi river. It was found that minimum of 30 cft/sec. flow must be discharged from Kadana reservoir.

It was anticipated that after panam project on panam tributary is complete and comissioned, the flow in panam river will reduce from 150 cft/sec. to 50 cft/sec. during summer months. Water quality degrades beyond limit in these conditions. These anticipated dissolved oxygen profiles using simulation model are not presented. For this anticipated conditions, flow augmentation was explored. The flow augmentation results are presented in Table 4.

Treatment Efficiency:

As explained earlier, biochemical oxygen demand or biodegradable organic matter content in the wastes from mini river donot have any significant effect on the dissolved

Table 4: Flow Augmentation Results.

Flow rate from cft./sec.		Minimum DO con- centration mg/l	Location of minimum DO river mile	Minimum $NH_3.N$ concn. mg/l
Kadana Reservoir	Panam Reservoir			
10.0	50.0	0.0	11.0	55.6
28.1	68.1	1.4	6.0	27.7
38.0	78.0	3.4	5.0	17.3
42.65	82.65	3.8	4.5	14.8
45.25	85.25	4.0	4.5	13.9

oxygen concentrations of Mahi river. It is the high concentrations of ammonia nitrogen which consumes considerable amount of dissolved oxygen and DO sag is observed beyond mile. 70. It was found that 1.0 percent ammonia stripping from the mini river waste would not allow the dissolved oxygen in river to fall below 4.0 mg/l.

Baroda Effluent Channel:

As discussed earlier, this channel was proposed to carry waste from industries which are discharging, at present, their liquid waste into mini river, to the estuarian region of Mahi river. Fig. 5.10 shows the anticipated dissolved oxygen profile after, this channel is commissioned. It was found that 30 percent of mini river waste can easily be

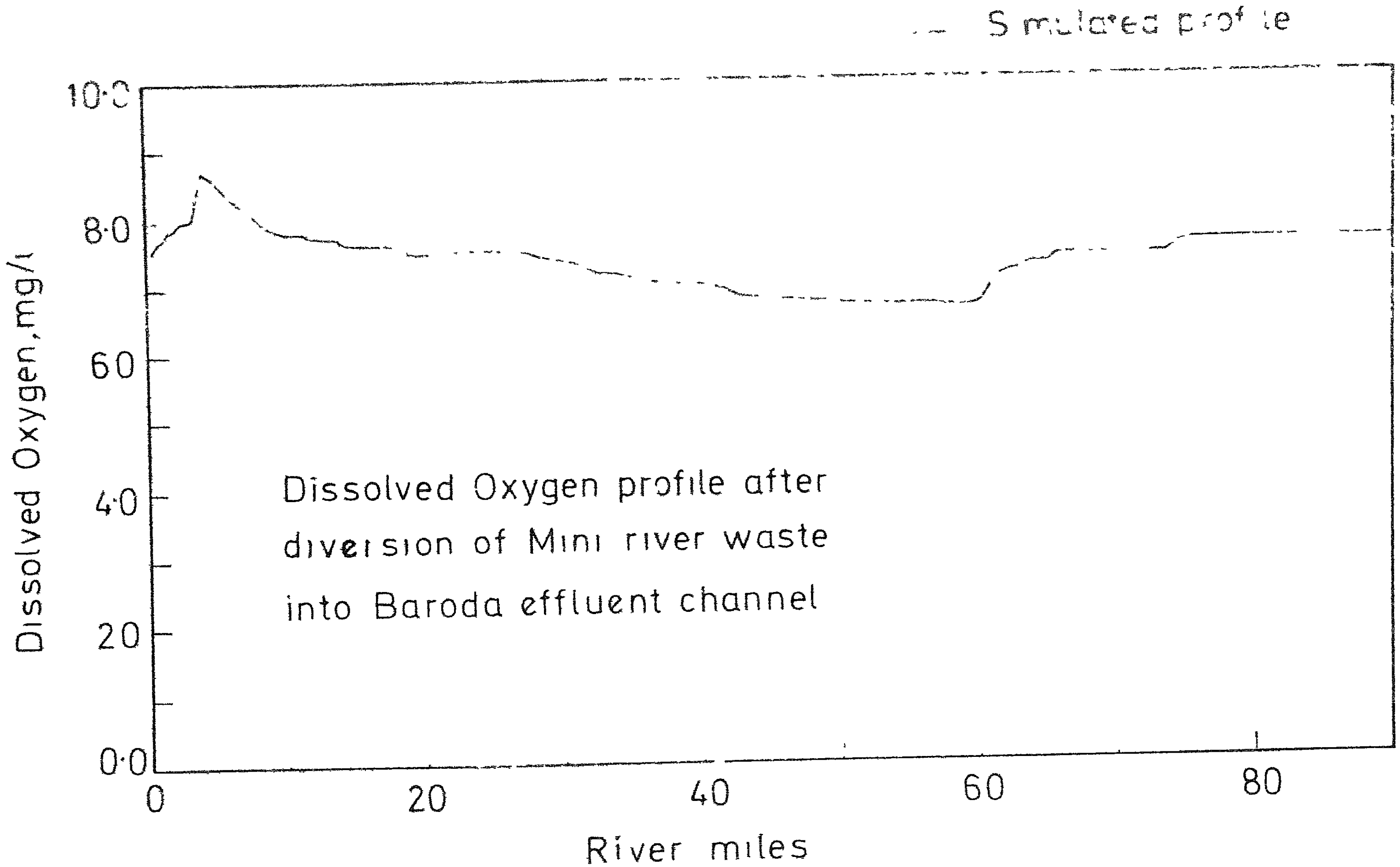

Simulated profile
10·0
8·0
6·0
4·0
2·0
0·0
Dissolved Oxygen, mg/l
0
20
40
60
80
River miles
Dissolved Oxygen profile after
diversion of Mini river waste
into Baroda effluent channel

Fig. 5·10

discharged into Mahi river even during critical months of summer. Thus, 30 percent reduction in designed capacity of Baroda effluent channel will result in considerable saving in its construction cost.

Chapter 6

CONCLUSIONS

Simulation studies for water quality in river Mahi indicates that classical Streeter Phelps' model for dissolved oxygen can not be applied where industrial wastes are discharged into river. If more reliable field survey data are available and properly used in such simulation models, a large saving in both time and money can be achieved.

It is concluded that minimum flow of 45.25 $ft.^3$/sec. from Kadana reservoir and that of 85.25 cft./sec. from Panam reservoir should be maintained to keep water quality in Mahi river above accepted standards.

1.0 percent treatment for ammonia removal from ~~m~~ Mini river waste can be exercised to upgrade the water quality in river Mahi.

30.0 percent reduction in design capacity of Baroda Effluent Channel can be achieved without affecting the water quality in river Mahi.

Recommendation for Future Work:

In the present study, all the state variables, which define the alternatives, like flow augmentation and treatment efficiency were studied separately. By making use of univariate methods of optimization, the best and optimal combination of these state variables can be computed using such simulation models.

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APPENDIX A

SOLUTION TECHNIQUE

Equation 4 can be written for a control volume or element, V_i, in the stream system as shown in Fig. 2.1 for nonuniform hydraulics as,

$$\frac{\partial c_i}{\partial t} = [(AD_L \frac{\partial c}{\partial x})_{i+\frac{1}{2}} - (AD_L \frac{\partial c}{\partial x})_{i-\frac{1}{2}}]/V_i$$
$$+ \frac{Q_{i-\frac{1}{2}}\, c_{i-1} - Q_{i+\frac{1}{2}}\, c_i \pm Qx_i\, cx_i}{V_i} + 'S_i'$$

where,

$V_i = \bar{A}_i \Delta x =$ volume of control element, ft.^{3},

$\bar{A}_i = \frac{1}{2}(A_{i-\frac{1}{2}} + A_{i+\frac{1}{2}}) =$ mean cross-sectional area of the control volume ft.^{2}

$(AD_L \frac{\partial c}{\partial x})_{i-\frac{1}{2}} =$ Total longitudinal dispersion of the constituent, ft.^{3}/sec.mg/l or temperature, ft^3/sec.-$^\circ$F, on the inflow side of the control volume,

$(AD_L \frac{\partial c}{\partial x})_{i+\frac{1}{2}} =$ Total longitudinal dispersion of the constituent, ft.^{3}/sec.mg/l or temperature, ft.^{3}/sec.-$^\circ$F, on the outflow side of the control volume,

$Q_{i-\frac{1}{2}} =$ Rate of flow into the control volume, ft.^{3}/sec,

c_{i-1} = Concentration of the constituent, mg/l, or temperature, ^oF, in the inflowing water.

$Q_{i+\frac{1}{2}}$ = Rate of flow out of the control volume, ft.^{3}/sec.

c_i = Concentration of the constituent, mg/l,

Qx_i = Local inflows or withdrawals, ft.^{3}/sec,

Cx_i = Concentration of the constituent, mg/l, or temperature, ^oF, in Qx, and

$'S_i'$ = Sources or sinks of a nonconservative constituent, mg/l, or temperature, ^oF

The form of the differential equation used in the numerical solution of the transport equation is similar to Eq. A-1, except written in a slightly different form,

$$\frac{\partial c_i}{\partial t} = [(AD_L \frac{\partial c}{\partial x})_i - (AD_L \frac{\partial c}{\partial x})_{i-1}]/V_i + \frac{Q_{i-1}\, c_{i-1} - Q_i\, c_i \pm Qx_i\, cx_i}{V_i} \pm 'S_i' \tag{A.2}$$

The resulting finite difference form of Equation (A.2) is,

$$-\left\{(AD_L)_{i-1} \frac{\Delta t}{V_i \Delta x} + Q_{i-1} \frac{\Delta t}{V_i}\right\} C^{n+1}_{i-1} + \left\{1.0 + [(AD_L)_i + (AD_L)_{i-1}] \frac{\Delta t}{V_i \Delta x} + Q_i \frac{t}{V_i}\right\} C^{n+1}_i - - (AD_L)_i \frac{\Delta t}{V_i \Delta x} C^{n+1}_{i+1} = Z_i \tag{A.3}$$

where,

$$Z_i = C_i^n + \Delta t \, 'S_i' + \Delta t \, Qx_1 \, cx_1 \tag{A.4}$$

$$V_i = \tfrac{1}{2} (A_1 + A_1 - 1) \; \Delta x = \text{volume of element } i, \tag{A.5}$$

and all other terms are as previously defined. All of the values on the right-hand side of Eqn. (A.3) are known at time step and all of those of the left-hand side are unknowns at time step n+1. The coefficients on the left-hand side can be given as,

$$a_i = (AD_L)_{i-1} \frac{\Delta t}{V_i \Delta x} - Q_{i-1} \frac{\Delta t}{V_i} \tag{A.6}$$

$$b_i = 1.0 + [(AD_L)_{i-1} + (AD_L)_i \frac{\Delta t}{V_i \Delta x} + Q_i \frac{\Delta t}{V_i}, \tag{A.7}$$

$$c_i = -(AD_L)_i \frac{\Delta t}{V_i \Delta x} \tag{A.8}$$

<u>Method of Solution:</u>

Equation (A.3) represents a tridiagonal set of linear equations for the solution of C_i^{n+1} for all i's. This can be represented in matrix form as,

$$\begin{bmatrix} b_1 & c_1 & & & & & & \\ a_2 & b_2 & c_2 & & & & & \\ & a_3 & b_3 & c_3 & & & & \\ & & \cdot & - & - & & & \\ & & & a_i & b_i & c_i & & \\ & & & & - & - & - - & \\ & & & & & a_{h-1} & b_{h-1} & c_{h-1} \\ & & & & & & a_h & b_h \end{bmatrix} \times \begin{bmatrix} C_1^{n+1} \\ C_2^{n+1} \\ C_3^{n+1} \\ \vdots \\ C_i^{n+1} \\ \vdots \\ C_{h-1}^{n+1} \\ C_h^{n+1} \end{bmatrix} = \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ \vdots \\ Z_i \\ \vdots \\ Z_{h-1} \\ Z_h \end{bmatrix} \tag{A.9}$$

An efficient method that readily lends itself to a computer solution of the set of Equation (A.9). The method of solution is as follows:

(1) Divide through the first equation in (A.9) by b_1 to obtain

$$C_1^{n+1} + W_1 \, C_2^{n+1} = G_1 \tag{A.10}$$

where,

$$W_1 \; c_1/b_1 \quad \text{and} \quad G_1 = Z_1/b_1 \tag{A.11}$$

(2) Combine Equation (A.10) and the first equation in (A.9), to eliminate a_2 and the result is,

$$C_n^{n+1} + W_2 \, C_3^{n+1} = G_2 \tag{A.12}$$

where,

$$W_2 = \frac{c_2}{b_1 - a_2 W_1} \quad \text{and} \quad G_2 = \frac{Z_2 - a_2 G_1}{b_2 - a_2 W_1} \qquad \text{(A.13}$$

(3) Combine Equation (A.12) and the third equation in (A.9) to eliminate a_3 and the result is,

$$C_3^{n+1} + W_3 C_4^{n+1} = G_3 \qquad \text{(A.14}$$

where,

$$W_3 = \frac{c_3}{b_3 - a_3 W_2} \quad \text{and} \quad G_3 = \frac{Z_3 - a_3 G_2}{b_3 - a_3 W_2} \qquad \text{(A.15}$$

(4) Proceed through the equations, eliminating a_i and storing the values of W_i and G_i given by,

$$W_i = \frac{c_1}{b_i - a_i W_{i-1}}, \quad i = 2,3,\ldots, h \qquad \text{(A.16}$$

and

$$G_i = \frac{Z_i - a_i G_{i-1}}{b_i - a_i W_{i-1}}, \quad i = 2,3,\ldots, h \qquad \text{(A.17}$$

(5) The last equation is solved for C_h^{n+1} by

$$C_h^{n+1} = G_h \qquad \text{(A.18}$$

(6) Solve for C_{i-1}^{n+1}, $C_{i-2}^{n+2}, \ldots,$ C_h^{n+1} by back substitution:

$$C_i^{n+1} = G_i - W_i C_{i+1}^{n+1}, \quad i = h-1, h-2, h-3, \ldots, 1.$$